

## ON THE ORIGIN OF EPISODIC ACCRETION IN DWARF NOVAE

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## ABSTRACT

We show that dwarf nova disks in quiescence have rather low magnetic Reynolds number, of order  $10^3$ . Numerical simulations of magnetized accretion disks suggest that under these conditions magnetohydrodynamic turbulence and the associated angular momentum transport is sharply reduced. This could be the physical origin of episodic accretion in dwarf nova disks. If so, the standard disk instability model needs to be revised.

*Subject headings:* accretion, accretion disks — MHD — turbulence — novae, cataclysmic variables

## 1. INTRODUCTION

It is a commonplace that resistive diffusion of magnetic fields is negligible in astrophysical plasmas. The importance of resistive diffusion can be measured via the magnetic Reynolds number

$$Re_M \equiv \frac{LV}{\eta},$$

where  $\eta$  is the resistivity, and  $L$  and  $V$  are a typical lengthscale and velocity, respectively.  $Re_M$  is often large in astrophysics because the length and velocity scales are large. For example, the decay time of magnetic fields in a sunspot, as estimated in the introduction to Parker (1979), is 300 yrs, implying a magnetic Reynolds number of order  $10^7$ . The decay time of magnetic fields in the center of the sun, or in the galactic disk, is even longer. In this letter we discuss an uncommon situation where  $Re_M$  is small and the decay time is short: dwarf nova disks in quiescence.

Dwarf novae (DN) are binary stellar systems in which a white dwarf accretes matter through an accretion disk from a main-sequence companion. DN go through regular, but not periodic, outbursts in which the luminosity of the disk increases sharply. They exhibit a rich and complex phenomenology, reviewed in detail by Warner (1995). DN are often regarded as “laboratories” for the study of astrophysical disk systems because they are bright, nearby, and have short characteristic timescales; changes in our understanding of these systems therefore have broad implications for other disk systems such as X-ray binaries, young stellar objects, and active galactic nuclei.

The significance of low  $Re_M$  in DN disks is connected to recent advances in the theory of angular momentum transport in disks. Balbus & Hawley (1991) showed that disks are linearly unstable in MHD, thereby revealing the long-sought-for instigator of disk turbulence. More recent work on convection and nonlinear hydrodynamic instability makes it seem unlikely that these once promising alternatives play any role in angular momentum transport in disks. Simulations of the nonlinear development of the Balbus-Hawley instability show that it transports angular momentum outward and acts as a dynamo in the sense

that it sustains a magnetic field in the presence of dissipation (see Balbus & Hawley (1997) for a complete review).

Most significantly, simulations by Hawley, Gammie, & Balbus (1996) (hereafter HGB) show that the nonlinear development of the instability is sensitive to the presence of resistive diffusion. A series of experiments in that paper shows that at  $Re_M \equiv L_z^2 \Omega / \eta = 10^4$  the magnetic field is depressed,<sup>2</sup> while at  $Re_M = 2000$  the magnetic field dies away, as does the angular momentum flux. This suggests that at  $Re_M \lesssim 10^4$  MHD turbulence and the associated angular momentum transport may die away. In this letter we show, using SS Cygni as a specific example, that  $Re_M$  is of order  $10^3$  in dwarf nova disks in quiescence.

In §2 we briefly summarize the standard disk instability model for DN outbursts. In §3 we estimate  $Re_M$  for SS Cygni’s disk in quiescence. In §4 we tentatively put forward a new limit cycle model for DN outbursts. We discuss the implications of these results in §5 and conclude in §6.

## 2. THE DISK INSTABILITY MODEL

Historically, a variety of mechanisms have been proposed to explain DN. The disk instability model, invoking an intrinsic modulation of the accretion rate in the disk, is now generally accepted as the explanation of DN outbursts (see Cannizzo (1993b) for a review and a discussion of the historical development of the subject). The essence of the mechanism is that the disk cycles between two states, a large accretion rate state (hot and mostly ionized) and a low accretion rate state (cold and mostly neutral). The disk cannot settle into a steady intermediate state because that state is thermally unstable.

The simplest version of the disk instability model, in which the angular momentum transport efficiency  $\alpha$  (introduced by Shakura & Sunyaev (1973)) is held constant throughout the cycle, does not work, however (e.g. Smak (1984)). Detailed time-dependent calculations show that, in order to obtain an outburst of sufficient amplitude,  $\alpha$  must vary between the hot and cold state. Researchers have been able to reproduce outburst light curves and mean times between outbursts using  $\alpha_{hot} \simeq 0.1$  and  $\alpha_{cold} \simeq 0.01$ . Another oft discussed possibility is that  $\alpha$  obeys a scaling relation such as  $\alpha = \alpha_0(H/r)^q$ , where

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<sup>2</sup>Notice that a different definition of  $Re_M$  is used in HGB.

$H$  is the disk scale height and  $r$  the local radius. To our knowledge this prescription has been used in the DN context only to study decay properties of the outburst light curves. Both these prescriptions for varying  $\alpha$  are phenomenologically motivated; while there exist some *post hoc* theoretical justifications for varying  $\alpha$ , in our view they are not strongly physically motivated.

### 3. RESISTIVITY IN SS CYGNI

What then is  $Re_M$  in dwarf nova disks? For definiteness, we focus on a nearby, well-studied system: SS Cygni. SS Cyg has a  $1.2 M_\odot$  white dwarf accreting from a disk fed by a  $0.7 M_\odot$  K5V companion, a period of 6.6hr, a distance from the primary to the L1 point of about  $6 \times 10^{10}$  cm, a mean interval between outbursts of 40d, and a characteristic decay time from outburst of 2.4d. The mean accretion rate is not well known but is of order  $10^{-9} M_\odot \text{ yr}^{-1}$  (Cannizzo (1993a)).

We require a temperature and density to estimate the resistivity in SS Cygni in quiescence. These are only weakly constrained by observations. In the absence of direct measurements, we must turn to a theoretical model for the disk evolution: the standard disk instability model. Future observations may provide better constraints on physical conditions in the disk.

SS Cyg has been theoretically studied in detail using the standard thermal limit cycle model (see Cannizzo (1993a) for the most detailed study to date). We have run our own evolutionary models of SS Cyg to estimate physical conditions in the quiescent disk, using a modern, time-dependent, implicit, adaptive grid code (Hameury et al. (1997)). We adopt the same parameters for SS Cyg as Cannizzo's standard model ( $\alpha_{hot} = 0.1$ ,  $\alpha_{cold} = 0.02$ ), and our calculated  $\Sigma$  and  $T_c$  are similar to those in his standard model. At a radius of  $2 \times 10^{10}$  cm from the primary a typical surface density in quiescence is  $200 \text{ g cm}^{-2}$ , and a typical central temperature is 3000 K. Then  $\Omega = 4.5 \times 10^{-3} \text{ s}^{-1}$ ,  $c_s = 3.5 \times 10^5 \text{ cm s}^{-1}$ ,  $H = c_s/\Omega = 7.7 \times 10^7 \text{ cm}$ , and  $\rho \simeq \Sigma/(2H) = 1.3 \times 10^{-6} \text{ g cm}^{-3}$ . In LTE hydrogen is then predominantly molecular. The disk is marginally optically thick in a Rosseland mean sense.

The resistivity is given by

$$\eta = \frac{c^2 m_e \nu_c}{4\pi n_e e^2},$$

where  $\nu_c$  is an effective collision frequency for electrons. Since electron-neutral collisions dominate, we take  $\nu_c = n_n \sigma_{en} v$ , where  $n_n$  is the neutral number density,  $\sigma_{en}$  is the electron-neutral momentum exchange cross section, and  $v = \sqrt{128kT/(9\pi m_e)}$ . At 3000 K  $\sigma_{en} = 1.3 \times 10^{-15} \text{ cm}^2$  (Hayashi (1981)). Then  $\eta = 1.67 \times 10^4 n_n / n_e$ . The electron abundance at this temperature is determined primarily by ionization of Na, and to a lesser extent, Ca and K (we assume solar abundances). A detailed solution for ionization equilibrium (we have used a code kindly provided to us by Dr. P. Hoeflich, but a simplified calculation involving Na, C, and K gives nearly identical results) gives  $n_n = 3.73 \times 10^{17} \text{ cm}^{-3}$ , and  $n_e = 8.53 \times 10^{11} \text{ cm}^{-3}$ , so  $\eta = 7.29 \times 10^9 \text{ cm}^2 \text{ s}^{-1}$ .

The natural length and velocity scales in disks are  $H$  and  $c_s$ , respectively. The disk magnetic Reynolds number is then  $Re_M \equiv c_s H / \eta$ . Using the resistivity just calcu-

lated,  $Re_M = 3670$ . This is below the value at which MHD turbulence is depressed in the simulations of HGB. Similarly low values of  $Re_M$  are obtained at other radii in our model. Of course, this  $Re_M$  was obtained assuming  $\alpha_{cold} = 0.02$ . At lower  $\alpha$  the disk will be cooler and denser, and then  $Re_M$  will be smaller since  $\eta$  is very sensitive to temperature. Since  $\alpha$  depends on the resistivity as well, there could be a runaway decay of MHD turbulence. All this suggests that, at least in SS Cygni, angular momentum transport may die away once the disk goes into quiescence.

Before going on, let us briefly consider two other issues. First, does ambipolar diffusion play any role? The relative importance of ambipolar diffusion and resistivity is controlled by the product of the electron and ion Hall parameters,  $DR = \omega_e \omega_i / (\nu_{en} \nu_{in})$ , where  $\omega_{e,i}$  are the ion and electron cyclotron frequencies and  $\nu_{in}$  is the ion-neutral collision frequency; when  $DR > 1$  ambipolar diffusion dominates. Assuming equipartition magnetic fields at our fiducial point in the SS Cyg disk, we find  $DR = 0.02$ . Since the field is likely to be weaker than this, resistivity dominates ambipolar diffusion.

Second, can nonthermal ionization save the day? Here the chief concern is X-rays; dwarf novae typically have  $L_x \simeq 10^{30} \text{ erg s}^{-1}$ , but SS Cyg is particularly bright in hard X-rays in quiescence, with  $L_x(1 - 37 \text{ keV}) \simeq 1.5 \times 10^{32} \text{ erg s}^{-1}$  (Yoshida et al. (1992)). Only photons with  $E \gtrsim 10 \text{ keV}$  will penetrate the disk. These will Compton scatter and diffuse downward into a layer of thickness  $\simeq 30 \text{ g cm}^{-2}$  corresponding to an effective optical depth of 1 (Glassgold et al. (1997), Igea & Glassgold (1997)). The intercepted flux per unit area of the disk is  $f_x \simeq L_x(H/r)/(4\pi r^2)$ . Suppose this flux diffuses into a layer of thickness  $H$  and produces 1 ion per  $E_i = 36 \text{ eV}$ . Then the volume ionization rate is  $\xi = L_x/(4\pi r^3 E_i) \text{ cm}^{-3}$ . Balancing this against dissociative recombination at a rate  $n_e^2 \times 8.7 \times 10^{-6} T^{-1/2} \text{ cm}^{-3}$ , we find  $n_e = 1.1 \times 10^9 \text{ cm}^{-3}$ . Since this is much less than the LTE electron number density we can neglect X-ray ionization in the bulk of the disk. It is possible, however, that a thin layer on the surface of the disk will be ionized by X-rays, and accretion will proceed in that layer in a manner similar to that described by Gammie (1996) in the context of protoplanetary disks. A thin partially ionized layer could explain eclipse maps of quiescent dwarf novae (Wood et al. (1992), Horne (1993)), which are interpreted as showing emission from a warm optically thin disk.

Suppose that MHD turbulence dies away in SS Cyg's disk in quiescence. It is possible that some weaker residual transport process will be present in the disk. Let us consider some of the possibilities. Convective turbulence is ruled out for at least two reasons: the disk is only marginally optically thick, so convection will not be present, and even if it were present, recent studies show that convective turbulence produces inward angular momentum transport (Ryu & Goodman (1992), Stone & Balbus (1996), Cabot (1996)). Turbulence due to nonlinear hydrodynamic instability also seems unlikely in light of recent analytic and numerical work (Balbus et al. (1996), Hawley & Balbus (1997)) which shows that nonlinear instability is simply not present in a Keplerian disk. Gravitational instability is ruled out, since for reasonable values of the surface density and of the "floor" temperature, set by irra-

diation of the disk by the secondary, hot spot, and primary, the disk has  $Q \gg 1$ . The remaining possibilities involve a spiral wave or shock, driven either by the companion's tidal field (Sawada et al. (1986); Spruit (1987)), or by a global linear instability (Papaloizou & Pringle (1984), Goldreich et al. (1986)).

The role of tidally driven spiral shocks is controversial (Rozyczka & Spruit (1993), Savonije et al. (1994); see also the claimed detection of spiral waves in IP Peg in outburst by Steeghs et al. (1997)). In our view, Savonije et al. have shown that a disk with small  $H/r$  and fixed mass couples only weakly to the tidal potential, and suffers no global instability. They have not, however, considered the interaction of the disk with the mass transfer stream. Since the incoming material has approximately constant specific angular momentum, which will be conserved in the absence of turbulent diffusion, it will accumulate in a partially pressure supported ring. This ring or torus may then suffer the Papaloizou & Pringle (1984) instability, or an allied global instability, as suggested by Rozyczka & Spruit (1993).

#### 4. A NEW LIMIT CYCLE?

The possibility of global hydrodynamic instabilities in DN disks leads us to tentatively propose a variant of the classical limit-cycle model for DN outbursts. In the hot state the evolution proceeds as usual until accretion causes the surface density to drop below the point where the disk can maintain the hot solution. The disk then cools, recombines, and forms molecular hydrogen. If the magnetic Reynolds number is low enough, then MHD turbulence will decay away. The disk then enters quiescence (the viscosity could even be as low as the molecular value, if no other angular momentum transport process is at work), and new material accumulates in a partially pressure-supported ring in the outer disk. Eventually this ring suffers a global hydrodynamic instability. The resulting shocks raise the central temperature of the disk, and hence  $Re_M$ , above a critical value. MHD turbulence sets in, raising the temperature still further and providing significant angular momentum transport. An outburst results. This idea is illustrated in Figure 1.

It remains to be seen whether this scenario can be integrated into a successful time-dependent model for the outburst. We suspect that at least one additional ingredient is required, and that is a modification of the classical diffusion equation for surface density in a viscous disk (e.g. Pringle (1981)). An important physical assumption underlying this equation is that the local stress adjusts instantaneously to a value specified by the current surface density and temperature. Simulations of HGB and Brandenburg et al. (1995) suggest that there is a relaxation time of many orbital periods as the stress adjusts to the current equilibrium value. To our knowledge, no study of time-dependent behavior in disks includes this effect.

#### 5. DISCUSSION

As a guide to where resistive effects become important in disks, we have calculated the temperature  $T_4$ , where  $Re_M = 10^4$ , as a function of surface density and rotation

frequency. The results are shown in Figure 2. A fit accurate to 5% is

$$\log(T_4) = 3.867 + 0.038 \log(\Sigma) + 0.20 \log(\Omega) + 0.01 \log(\Omega)^2,$$

where  $\Sigma$  and  $\Omega$  are expressed in  $\text{g cm}^{-2}$  and  $\text{s}^{-1}$  respectively. Notice that, for a given value of  $\alpha$  and for realistic opacities not all regions of this plot are accessible. In particular, disks in the upper right corner are unlikely to be cool enough to reach  $T_4$ .

The above discussion is predicated on the idea that MHD turbulence in disks decays below a critical  $Re_M$  of order  $10^4$ . This is consistent with the evidence from numerical simulations, but cannot be regarded as firmly established given the small number of simulations that have been done to date and their low numerical resolution.<sup>3</sup> One possible complication is that saturation may depend on magnetic Prandtl number  $Pr_M \equiv \nu/\eta$  rather than simply on  $Re_M$  (Batchelor (1950)); here  $\nu$  is the microscopic viscosity. The sense of the theoretical argument is that when viscosity is larger than resistivity the field builds up, while in the opposite limit the field dies away. Counterintuitively, this argument suggests that  $\alpha$  should increase as  $\nu$  increases. There is weak evidence for this from the simulations in that those with larger *artificial* viscosity saturate with slightly larger  $\alpha$ . Since microscopic viscosity in disks is small compared to the numerical and artificial viscosities present in the simulations, there is the possibility that MHD turbulence may decay at even higher temperatures than we have indicated. Clearly there are many unanswered questions about the saturation of disk turbulence that might profitably be addressed by future numerical simulations, with the promise of direct application to astronomically interesting systems such as DN.

Several characteristics of the new limit cycle are worth mentioning here. First, our model bears some resemblance to that of Armitage et al. (1996), who speculated that MHD turbulence would cease as DN enter quiescence because the magnetic field would become superthermal. Our physical mechanism is, however, different and less speculative. We expect the field to resistively decay, rather than being frozen in and dynamically dominant. Second, in our scenario the outburst is triggered rather differently than in the disk instability model. Assuming that turbulence exists above a critical  $Re_M$  outburst should begin when the disk rises above a critical temperature, not when the disk becomes thermally unstable. Third, the details of the outburst will be sensitive to metallicity, or at least the abundance of Na, because  $\text{Na}^+$  provides most of the free electrons at low temperatures. Finally, preliminary calculations suggest that the model is applicable to X-ray binaries, although disk irradiation could complicate matters somewhat.

#### 6. CONCLUSION

We have argued that MHD turbulence and the associated angular momentum transport may die away in dwarf novae in quiescence. If there are no other significant sources of angular momentum transport in disks, then this is the physical origin of episodic accretion in dwarf novae.

<sup>3</sup>The critical value of the resistivity, if any, must be determined from nonlinear theory. Linear theory says that stability is recovered at a value of the resistivity that depends on the field strength. Absent an almost thermal external field, however, the field strength in the disk is determined by the nonlinear outcome of the instability itself.

We have proposed a scenario in which a global hydrodynamic instability heats the outer disk, thereby raising the conductivity and initiating the outburst. This scenario is a modification of the standard disk instability model that provides a physical explanation for episodic accretion yet retains many of the standard model's most attractive features.

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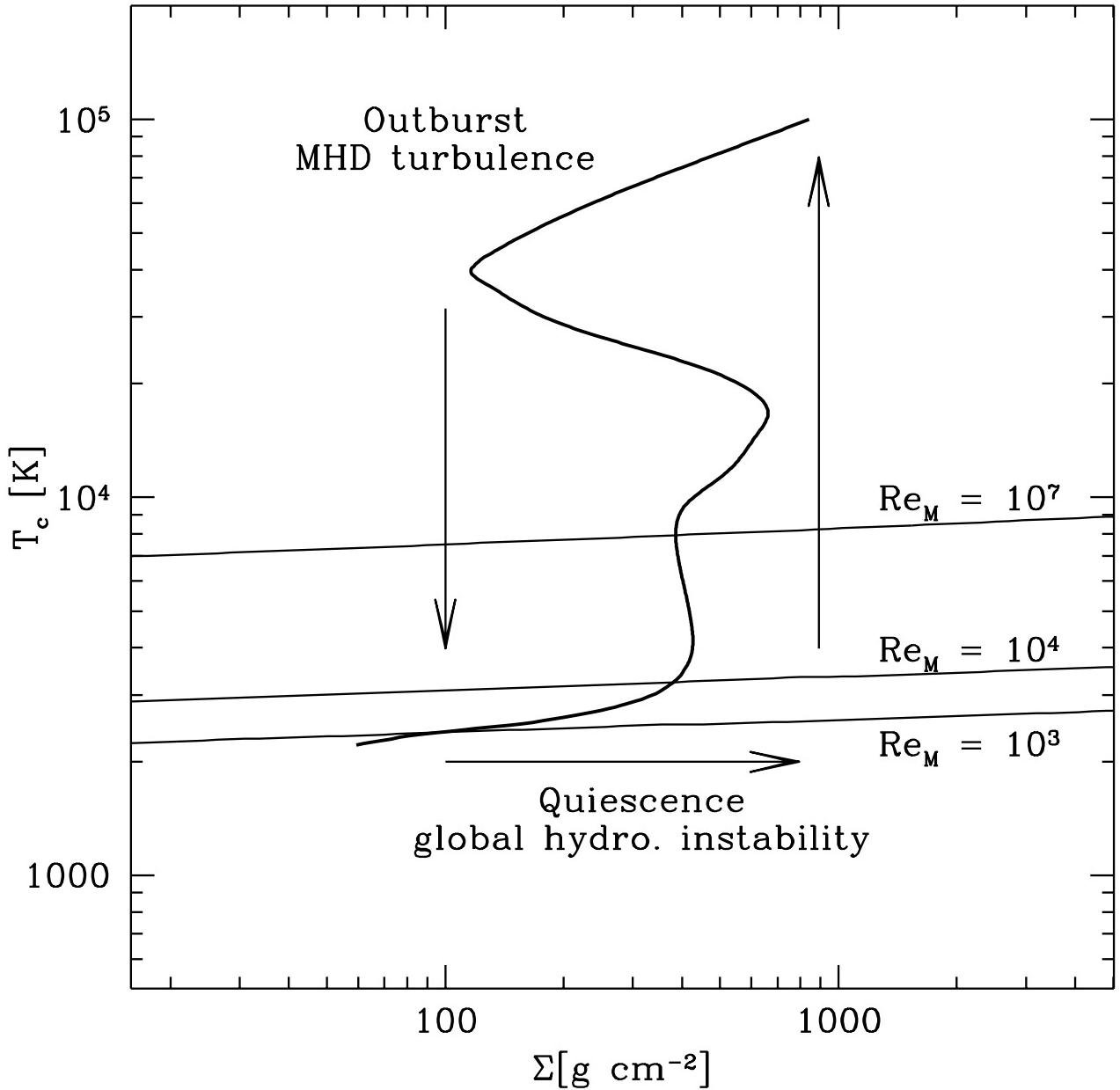


FIG. 1.— A schematic of the proposed outburst cycle. The solid line (“S-curve”) shows the thermal equilibrium solution for the disk in SS Cygni at radius  $r = 2 \times 10^{10}$  cm, using the standard assumption of  $\alpha = 0.1$  on the hot branch and  $\alpha = 0.02$  on the cold branch (the transition temperature is  $2.5 \times 10^4$  K). Our estimates show that when the disk “falls off” the hot branch, it will pass through the line marked  $Re_M = 10^4$ , where MHD turbulence dies away. The disk is then passive, and is reactivated only by a global hydrodynamic instability.

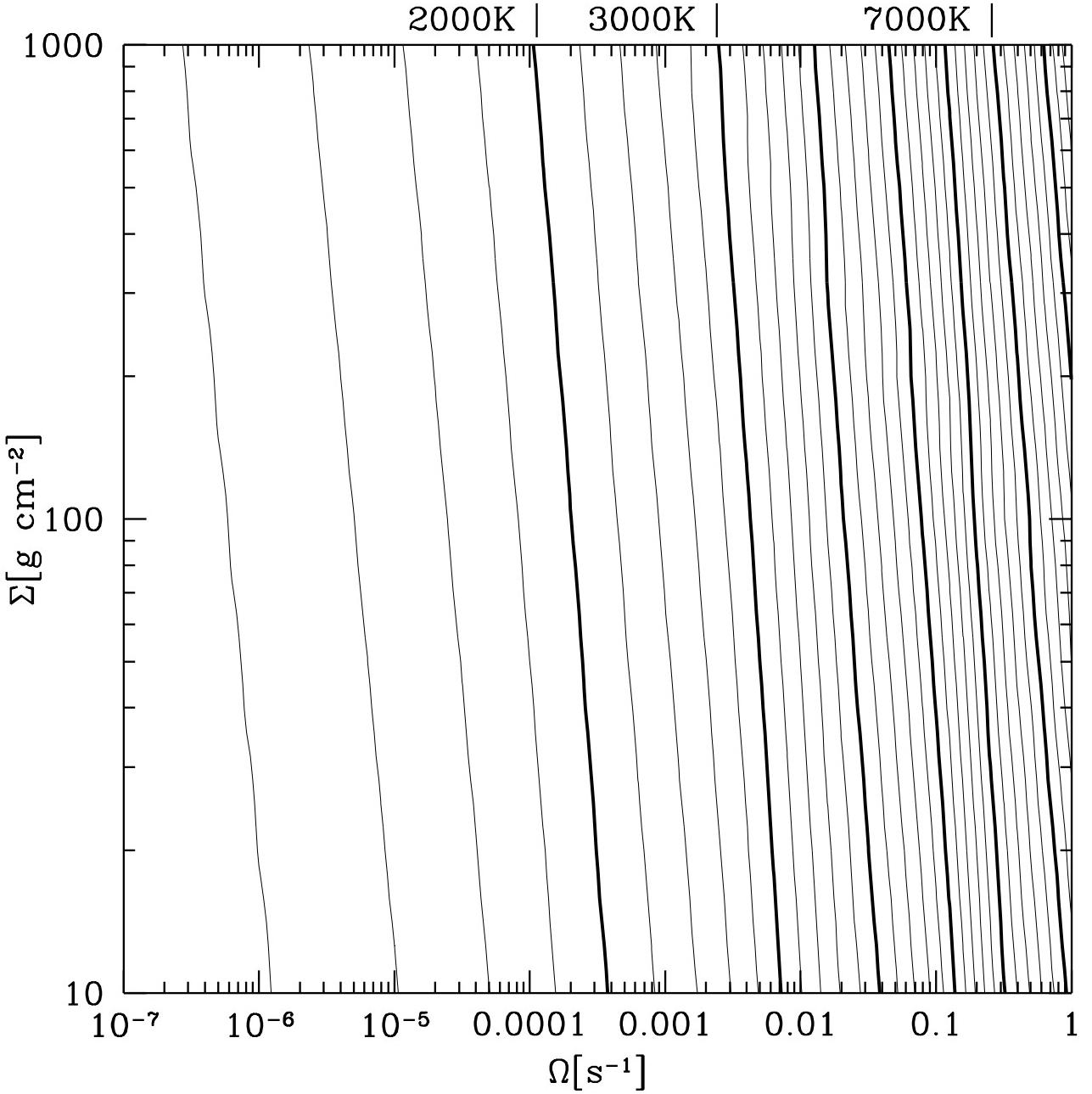


FIG. 2.— The temperature  $T_4$  where  $Re_M = 10^4$ , as a function of rotation frequency and local surface density. The heavy solid lines are spaced at intervals of  $10^3\text{ K}$ , the light lines at intervals of  $200\text{ K}$ . Recall that at  $T > T_4$ ,  $Re_M > 10^4$ .